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SUSTAINABLE DEVELOPMENT

Life cycle cost analysis of three renewed street lighting installations in Finland

Leena Tähkämö · Anne Ylinen · Marjukka Puolakka · Liisa Halonen

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Abstract
Purpose Outdoor lighting is facing major changes due to the EU legislation on ecodesign of energy-related products, such as the ban of high-pressure mercury (HPM) lamps widely used in outdoor lighting. This article presents life cycle costs (LCC) of three examples of replacing HPM lamps in street lighting in Finland. The purpose of the article is to assess how the development of light-emitting diode (LED) technology affects LCCs and how the division of LCCs differentiates in the cases.
Methods Two of the cases change from HPM lamps to high-pressure sodium (HPS) lamps. In the third one, HPM lamps are replaced by LED luminaires. LED technology predictions of price and luminous efficacy are included in different scenarios. The calculations consider investment and operating costs and residual value.
Results and discussion Each replacement reduces the energy costs approximately by half compared to the original HPM lamp luminaires. Energy costs dominate the LCCs of the HPS lamp installations while investment cost is the dominating one in LED luminaire case. The changes from HPM to HPS technology have payback times lower than 9 years, while changing to LED luminaires is not economic. However, the electricity price is low in this case. The payback times of LED installations can be as low as 6 years if the luminaires are installed in 2015 and an average electricity price is used.
Conclusions The LCCs of real-life case studies cannot be directly compared, since their luminous properties vary. There is a need for a method for including luminous properties in LCC calculations.

Keywords LED · Life cycle costs · Light-emitting diode · Payback time · Road lighting · Street lighting

1 Introduction

Outdoor lighting in Finland has recently been forced to start radical changes to comply with the requirements of the legislation in the European Union (EU). The most significant change concerning outdoor lighting is the ban of high-pressure mercury (HPM) lamps in April 2015. In Finland, this means that about half of the outdoor luminaires need to be changed from HPM lamps to other light source technologies. In the EU, there were approximately 18 million HPM lamps in use in 2007 resulting to a major European-wide replacement work (Van Tichelen et al. 2007).

As street lighting is undergoing a major change, it is useful to assess replacement options and possibilities of current light sources. This article illustrates the replacement work from the life cycle cost (LCC) point of view. LCCs are analysed in three cases of street lighting installations in Finland. In two cases, conventional HPM lamps are replaced by high-pressure sodium (HPS) lamps, and in one case, by light-emitting diode (LED) luminaires. LCCs from the purchase till the end of operating time, including the investment costs, operating costs and the residual value, are taken into account from the point of view of the municipalities, i.e. the buyer and the user of the installation. The calculations include the present value of LCC and the payback time. The division of LCCs is presented in each case, and the effect of the development in LED technology on LCCs is assessed in scenarios.

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L. Tähkämö (✉) · A. Ylinen · M. Puolakka · L. Halonen
Lighting Unit, School of Electrical Engineering, Aalto University,
P.O. Box 13340, 00076, Aalto, Finland
e-mail: leena.tahkamo@aalto.fi

2 Street lighting in Finland

Street and road lighting contribute to traffic and pedestrian safety, and it is a notable energy consumer. In Finland, outdoor lighting consumes annually approximately 800 GWh of energy (Sippola 2010). Street and road lighting installations have long lifetimes, about 30 years, and the annual operating time is approximately 4,000 h. Lamps are replaced mainly in groups in 3- or 4-year intervals. Spot replacements are done only occasionally.

In Finland, street and road lighting is designed by using the national guidance based on the European standards EN 13201:2-4 and a technical report EN 13201:1 (European Committee for Standardization 2003, 2004; Finnish Road Administration 2006). The design criteria for roads with motorised traffic are based on six lighting classes: AL1, AL2, AL3, AL4a, AL4b and AL5. Photometric criteria are set for each lighting class in order for the road lighting to fulfil the visual needs of road users. The recommendations for the quantity and quality of light include average road surface luminance (L_{ave}), overall and longitudinal uniformities of road surface luminance (U_o, U_l), surround ratio (*SR*), and threshold increment (*TI*). Road lighting design, whether it is related to a renovation of an existing installation or to building a new one, is based on the recommendations.

EU legislation sets requirements on products used in street and road lighting. The EU regulation 245/2009 amended by regulation 347/2010 sets requirements for fluorescent lamps, high-intensity discharge lamps, and their ballasts and luminaires, which are commonly used in tertiary sector, e.g. in offices, commercial and industrial lighting, and street, road and other outdoor lighting. The regulation aims at improving the environmental performance of the products. The old, inefficient lighting products shall be replaced by products complying with the requirements on efficiency, functionality and product information. The most significant effect of the ecodesign legislation on outdoor lighting is the ban of the HPM lamps from 13 April 2015.

There are several alternatives for replacing HPM lamps in outdoor lighting: HPS lamps, metal halide (MH) lamps, induction lamps and LED luminaires. Fluorescent lamps are rarely used outdoors in Finland. The change from HPM lamp technology requires replacing of not only the lamp but also the ballast and the luminaire. The ballast of HPM lamp cannot operate other lamp types, and the HPM lamp luminaire is usually unsuitable to accommodate lamps of other dimensions. However, there is an exception, a so-called retrofit HPS lamp, on the market that can be installed to replace directly HPM lamps, as they are able to operate on the ballast of HPM lamp. However, the placing on the market of retrofit HPS lamps is banned simultaneously with HPM lamps in 2015.

The most probable replacement option for HPM lamp is the standard HPS lamp due to its luminous efficacy of approximately 50 to 150 lm/W, maturity as a technology, relatively long lifetime of 10,000 to 30,000 h and affordable purchase price (Kitsinelis 2011). Low-pressure sodium (LPS) lamp is not recommended as a replacement option for outdoor lighting despite the high efficacy of the lamp, up to 200 lm/W, because the colour of the LPS lamp is orange, making colour vision impossible. MH lamps are a potential option with their white light and colour rendering index ranging from 70 to 90. However, MH lamp costs approximately three times the price of an HPS lamp, and the lifetime of MH lamps is short for a streetlight, about 10,000 h. Induction lamps have a very long lifetime, up to 100,000 h, and they produce white light. The high purchase price of induction lamps hinders their more frequent use. LED technology is starting to penetrate the outdoor lighting market with high-power LED luminaires. There are high expectations towards LED technology, although there are uncertainties regarding many of their characteristics, such as lifetime, lumen maintenance and colour shift. The purchase price of outdoor LED luminaires is approximately three to four times the price of an HPS streetlight luminaire. The luminous efficacy of LED chip has exceeded 200 lm/W in the laboratory, but the one of LED luminaires currently on the market is usually between 50 and 100 lm/W. The price of LED luminaires is sinking as the LED technology becomes more frequently used and the production costs are reduced. LED technology is not considered fully mature for outdoor purposes due to the problems regarding glare and heat extraction of high-power LED luminaires.

Outdoor lighting in Finland is dominated by HPM lamps (Fig. 1). HPM lamps cover approximately 51%, HPS lamps 45%, and MH lamps 1.8% of outdoor lighting (Sippola 2010). The rest (2.2%) of the 1.3 million outdoor

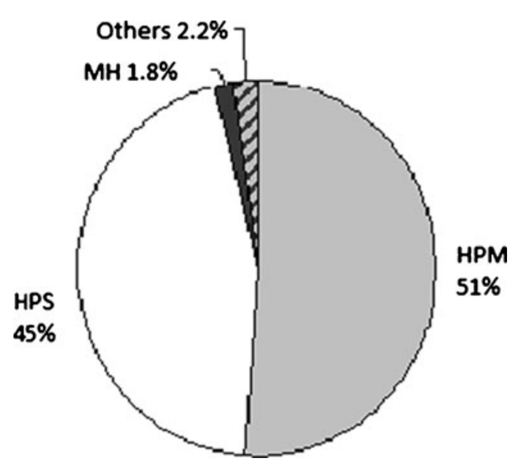

Fig. 1 The share of lamp types in outdoor lighting in Finland (Sippola 2010)

luminaires comprise of LPS lamps, induction lamps, fluorescent lamps and LED luminaires (Sippola 2010). This shows the need for a major replacement work, as about 660,000 HPM lamps need to be replaced by more efficient light sources in a few years, since new HPM lamps cannot be placed on the EU market after April 2015.

2.1 Predictions of LED development

The development in LED technology is expected to be fast regarding purchase price and luminous efficacy. There are multiple possibilities to estimate the price development of LED technology: one can estimate the price of a LED chip, predict the manufacturing costs of the entire LED luminaire, or proportion the price to lumen output of LED package. Similarly, the luminous efficacy predictions can be conducted in different methods, e.g. concentrating on efficacy of the chip or a luminaire. Table 1 presents luminous efficacy and price predictions for cool and warm white LED packages. Cool white LEDs are used in street lighting due to their higher lumen output.

However, there are also more conservative estimates on LED development, e.g. regarding LED manufacturing costs, or best commercial high-power LED luminaire. Compared to year 2010, the manufacturing costs of LED luminaire are estimated to be reduced by 24%, 49% and 74%, respectively, in 2012, 2015 and 2020 according to US DOE (2010b). Luminous efficacy of high-power cool white LED products (luminaires) is predicted to be in 2012 only 17% higher compared to 2010 (Strategies Unlimited 2009). Thus, the LCC calculations include more conservative estimates of the development of LED price and efficacy than indicated in Table 1.

3 Life cycle cost analysis

Life cycle costing can be conducted from different point of views: supplier, producer, user or society (Swarr et al. 2011). In this article, the approach is the municipalities, who install and use the street lighting. Norris (2001) recommends integrating the environmental and economic assessments to understand the life cycle effects as a whole, since presenting only the environmental life cycle assessment (LCA) results does not convince the actors in private sector. Swarr et al. (2011) adds the social aspect, so that a full LCA would include environmental, economic and social aspects.

The LCC assessment is carried out in a similar procedure as LCA including four components: goal and scope definition, inventory analysis, interpretation and reporting (Swarr et al. 2011). There are various ways of conducting an LCC assessment. In principle, LCC takes into account all costs from manufacturing, design, transport, instalment, use and disposal. However, some life cycle phases are neglected depending on the point of view of the assessment. The conventional cost accounting includes life cycle aspects, such as raw material costs, but usually neglects all end-of-life costs such as costs from waste disposal and recycling (Swarr et al. 2011). This article is considered as an environmental LCC that includes initial investment, operating costs and end-of-life costs. The purchase price is part of initial investment, and it reflects the costs of research, development and manufacturing. The costs of environmental protection are considered to be at least partially included in the purchase price. End-of-life costs, such as dismantling costs, are estimated in the residual value.

3.1 Goal and scope definition

The goal of the LCC study is to compare the costs occurring during the life cycle of renovated street lighting installations including purchase price, operating costs and residual value. The intention is to show the distribution of the costs in the life cycle, to proof whether it is economic to update streetlights from HPM lamps and to assess the effect of LED technology development on LCCs in different scenarios. The scope is the Finnish street lighting with three exemplary cases (A, B and C) in Southern Finland. Cases A and B are located in a municipality of Kotka, and case C in

Table 1 Predictions of LED price development and luminous efficacy

Product	Quantity	2010	2012 compared to 2010 (%)	2015 compared to 2010 (%)	2020 compared to 2010 (%)
Cool white LED package	Efficacy (lm/W)	134	+29	+60	+81
Cool white LED package	Price ($/klm)	13	−54	−85	−92
Warm white LED package	Efficacy (lm/W)	88	+45	+109	+166
Warm white LED package	Price ($/klm)	25	−56	−87	−96

LED package refers to an assembly of one or more LED chips including the mounting substrate, encapsulant, phosphor, electrical connections, and possibly optical components and thermal and mechanical interfaces. Cool white LED package produces light with CCT from 4,746 K to 7,040 K and R_a 70–80, and warm white 2,580–3,710 K and R_a 80–90 (US DOE 2010a)

Kerava. The study is conducted from the perspective of the users, i.e. the municipalities. The LCC of three cases are compared on the basis of functional unit of 1 km of illuminated street, as €/kilometre is the established unit in cost analysis of street and road lighting.

In street and road lighting, it is essential to consider the quality of light due to its importance in traffic safety. The Finnish recommendations for road lighting are used as design criteria, but they are not mandatory. It is noted that not all installations in use fulfil the recommendations. The luminous properties of the cases are compared by simulating them in DIALux software. DIALux models only straight roads, and all the objects, such as trees and buildings, are excluded. The results are presented in Table 2. None of the three cases fulfil the design criteria totally. The pole distance is not optimal in the cases. As there is no method for including the fulfilment of the design criteria in the LCC calculations, they are calculated by using the unit €/kilometre.

The old luminaires were not measured regarding all of the properties, and it was not possible to measure at all the case C. The average road surface luminance was measured with old lamps in cases A and B, 0.06 and 0.35 cd/m^2, respectively, and found to not by far to fulfil the design criteria. This was due to the poor performance of the old luminaires and the aging of the plastic cover of the luminaires. The replacement changed the colour of the light in cases A and B from cool white to yellowish, but in case C, it remained cool white. The colour rendering of the lighting was improved in case C from R_a=40 to R_a=76.

3.2 Life cycle inventory

The initial installations of all three cases were HPM lamps, which were replaced in 2009–2010. In each case, there is one luminaire per pole. In case A, 400 pieces of 125 W HPM lamps in a residential area were replaced by 50 W HPS lamps. Case B contains 60 pieces of 250 W HPM lamps replaced by 100 W HPS lamps on a collector road. In case C, 14 pieces of 125 W HPM lamps were replaced by LED luminaires in a residential area. Additionally in case C, the poles, pedestals and cables were renewed at the same time with the luminaires. The additional costs from pole or other replacements are not included in the calculations in order for the three cases to be equally treated.

Case C includes a group replacement of LED luminaires after 18 years of use according to the manufacturer's information on lifetime. The price of LED luminaire is estimated to be reduced by 85% in 18 years while the installation cost, 70 € per luminaire, is estimated to be constant. Labour expenses will probably rise in 18 years, but on the other hand, new luminaire may be easier and

Table 2 Values calculated with DIALux, the recommended limits of the street lighting cases in Finnish national guidance and an indication whether the calculated value fulfils the limit (Y/N)

Case (class)	L_m (cd/m^2)			U_o			U_l			*TI* (%)			*SR*			U_o (wet)		
	Calc	Limit	Y/N	Calc	Limit	Y/N	Calc	Limit	Y/N	Calc	Limit	Y/N	Calc	Limit	Y/N	Calc	Limit	Y/N
A (AL4b)	0.59	≥0.75	N	0.0	≥0.4	N	0.2	≥0.4	N	13	≤15	Y	0.5	≥0.5	Y	0.01	≥0.15	N
B (AL3)	1.0	≥1.0	Y	0.3	≥0.4	N	0.6	≥0.6	Y	10	≤15	Y	0.5	≥0.5	Y	0.06	≥0.15	N
C (AL5)	0.6	≥0.5	Y	0.2	≥0.4	N	0.2	≥0.4	N	24	≤15	N	0.6	≥0.5	Y	0.03	≥0.15	N

Calc calculated; *Y/N* Yes/No

faster to install. Calculations include also the improvement of the luminous efficacy of LED luminaire so that less power is needed to produce the same luminous flux with a future luminaire. Luminous flux is not included per se in calculations. Spot replacements of LED luminaires are not included, since they would distort the calculations. The purchase price of a single LED luminaire is even higher than the purchase price of a batch of luminaires.

The LCCs are calculated by using the present value method. All the returns and costs are discounted to present time by using the rate of interest. The present value of the LCCs is calculated as follows:

$$\mathrm{LCC} = C_\mathrm{i} + \left(\frac{1-(1+i)^{-n}}{i}\right)C_\mathrm{o} + \frac{\mathrm{RV}}{(1+i)^n} \tag{1}$$

where C_i is the sum of investment costs, i the rate of interest, n the number of years, C_o the operating costs and RV the residual value (Finnish Road Administration 2006). Investment costs include all the initial investment costs of construction, such as the purchase of lamps, ballasts and luminaires, and installation costs. The operating costs include all the annual costs of operation such as energy and maintenance costs. Energy costs include the electricity costs. Maintenance costs cover lamp replacement costs, other repair and replacement costs, and cleaning and upkeep costs, if any. The operating costs in the case study include electricity costs and lamp replacement costs. The RV represents the return or cost that can be received of the investment after the service time. The residual value is negative if there is a profit from the end of life of the product and positive if it creates costs. In street lighting installations, the residual value is estimated to be 25% of the investment costs (Finnish Road Administration 2006). As the service period of street lighting is long, approximately 30 years, the present value of the RV remains somewhat low.

Payback times are calculated in two ways: a simple and a more profound method (Fuller and Petersen 1996). The simple payback time (SPB) is calculated for a renovation installation by dividing the investment costs by the savings in annual operating costs. SPB is used when the operating costs are assumed to remain constant each year, the time value of money is not included and only annual operating costs exist. Neither price escalation nor inflation is considered.

The simple payback time cannot be used if it is necessary to consider the annual growth of operating costs due to inflation or escalation. It is recommended to discount the future costs if the duration of the product system exceeds 2 years (Swarr et al. 2011). Then, discounted payback time (DPB) needs to be used. In case of the DPB, the investment costs equal the savings from the discounted operating costs. The formula of DPB (Bhandari 2009) is calculated as follows:

$$\mathrm{DPB} = \frac{-\ln\left(1-\frac{iC_\mathrm{i}}{C_\mathrm{o,old}-C_\mathrm{o,new}}\right)}{\ln(1+i)} \tag{2}$$

where $C_\mathrm{o,\ old}$ is the operating costs of the old installation and $C_\mathrm{o,\ new}$ the ones of the new installation. Both SPB and DPB are used in this LCC, since, on the one hand, the duration of street lighting system well exceeds 2 years (30 years); but on the other hand, the DPB cannot be calculated in every case.

3.2.1 Base cases

The base cases A, B, and C describe the street lighting installations. Most of the information on the cases presented in Table 3 was collected from the maintenance engineers of the municipalities. Nominal discount rate, inflation, real discount rate and the time scale of the calculation based on a publication by the Finnish Road Administration (2006). The luminaire power is measured in Aalto University Lighting Unit. The electricity prices exclude taxes.

The purchase cost of luminaire includes the instalment costs. Instalment costs contain also the dismantling of the old installation, as it is dismantled at the time as the new luminaire is installed, and the dismantling costs are not separated in the data. Three cases have common quantities, such as the nominal discount rate (6%) and inflation (3%) resulting to a real discount rate (2.91%), time scale of the calculation (30 a) and value-added tax (VAT, 0%).

The information on the replacements has been given in two ways. In cases A and B, the replacement costs are calculated on the basis of the group and spot replacement costs while in case C, the maintenance costs of the old installation are presented as overall annual maintenance costs. The group replacement of LED luminaire is estimated to occur in 18 years. Spot replacements of LED luminaires are not taken into account in calculations.

3.2.2 Variant cases

Four variant cases take the future development of LED technology into account by different instalment and replacement scenarios. Case C is used as a reference case, and the future predictions are compared to year 2010 values. The calculations include more cautious estimates than predictions estimated by US DOE (2010a, see Table 1), since less dramatic predictions are also presented (Strategies Unlimited 2009). On the average, the luminous efficacy of cool white LED luminaire is estimated to increase by 20% in 2010–2012, by 50% in 2010–2015, and by 75% in 2010–2020. The price development of LED

Table 3 Information on the street lighting cases A, B and C

Quantity	Unit	Case A	Case B	Case C
Pole spacing, average	m	26	32	30
Number of lamps	pcs	400	60	14
Operating time	h/a	4,000	4,000	4,000
Electricity price (electricity + transmission)	€/kWh	0.082	0.082	0.045
Old installation				
Lamp type		HPM 125 W	HPM 250 W	HPM 125 W
Measured luminaire power	kW	0.140	0.284	0.140
Lamp group replacement period	a	3	3	3
Group replacement cost	€/pcs	13.13	15.90	–
Spot replacement cost, additional cost	€/pcs	33	36	–
Amount of spot replacements	%	2	2	–
Maintenance costs, overall	€/pcs, per annum	–	–	13.68
New installation				
Lamp/luminaire type		HPS 50 W	HPS 100 W	LEDway Road 30
Measured luminaire power	kW	0.063	0.114	0.060
Luminaire power in 2020	kW	–	–	0.034
Lifetime of the lamp/luminaire according to manufacturer	h	16,000	16,000	75,000
Lamp replacement period, assumption	a	4	4	18
Purchase cost of the luminaire including instalment costs	€/pcs	192	294	791.29
Group replacement cost	€/pcs	18.5	19.5	178.19
Spot replacement cost, additional cost	€/pcs	40	43	–
Amount of spot replacements	%	2	2	–

luminaire is estimated to decrease by 40%, 65% and 85%, respectively. Electricity price in the variant cases is the average in municipalities in Finland 0.095 €/kWh (Association of Finnish Local and Regional Authorities 2010).

The information on the four LED variant cases is collected in Table 4. Variant cases have the same pole spacing, number of poles, operating time, discount rates, time scale and VAT as case C. The operating costs of new installations are calculated as an average for 30 years. The reduction in power consumption thanks to the improvement of luminous efficacy is taken into account when luminaires are replaced.

Each variant represents a certain scenario including the development in luminous efficacy and purchase price of LED luminaire. Variant 1 includes the installation in 2010 and the group replacement after 18 years of use based on the lifetime given by the manufacturer. Thus, variant 1 corresponds to case C the only exception being the electricity price. To see the effect of LED price decrease on LCCs, variants 2 and 3 are installed in 2012. Variant 2

Table 4 Information on the new installation of LED street lighting variants and case C

		Variant 1	Variant 2	Variant 3	Variant 4	Case C
Time of installation and group replacement		2010, 2028	2012, 2030	2012, 2015	2015	2010, 2028
Quantity	Unit					
Measured/calculated luminaire power	kW	0.060	0.050	0.050	0.040	0.060
Estimated luminaire power at the time of group replacement	kW	0.034	0.034	0.040	–	0.034
Lifetime of the luminaire according to manufacturer/estimated lifetime	h	75,000	75,000	>75,000	>75,000	75,000
Lamp replacement period, assumption	a	18	18	–	–	18
Purchase cost of the luminaire including instalment costs in the time of group replacement	€/pcs	791.29	502.77	502.77	322.45	791.29
Group replacement cost	€/pcs	178.19	178.19	322.45	–	178.19

Table 5 Results of LCCs of street light renovation cases including change from HPM to HPS lamp (cases A and B) and from HPM to LED luminaire (case C)

Quantity	Unit	Case A	Case B	Case C
Investment costs (luminaires)	€/km	7,380	9,190	26,380
Operating costs, old	€/km, per annum	1,970	3,110	1,300
Operating costs, new	€/km, per annum	1,020	1,360	630
Residual value, calculated	€/km	1,850	2,300	6,590
Present value of life cycle costs	€/km	28,340	37,120	41,600
Simple payback time	a	8	5	40
Discounted payback time	a	9	6	–

includes the replacement of LED luminaires after 18 years. In variants 1 and 2, likewise in case C, the power and purchase price in 2028 or 2030 are estimated on the basis of 2020 technology predictions due to the lack of estimates that would cover time scale up to 2030. In variant 3, the development of LED luminaire is considered to be so fast that the installation is renewed as soon as after 3 years, in 2015. This scenario represents the possibility to renew the installation sooner than the end of operating life of LED luminaire in order to utilize the development. Variant 4 includes the installation in 2015, after which no group replacements are needed due to the assumption of development in lifetime. The challenges of LED technology, such as the heat transfer, are expected to be solved by 2015 providing longer lifetimes of LED luminaires.

4 Results

4.1 Base cases

The LCC results of the cases A, B, and C collected in Table 5 show that case C differs significantly from the cases A and B with its expectedly high investment costs. It is noted that the cases are not equal in luminous properties, so LCCs cannot be quantitatively compared. Originally, same lamp types were used in cases A and C, 125 W HPM. The annual operating times were also the same. Despite of the similarities, the operating costs of the old installations differ, 1,970 €/km in case A and 1,300 €/km in case C, due to different electricity prices, 0.082 €/kWh in case A and 0.045 €/kWh in case C, and pole distances, 26 and 30 m, respectively. Operating costs of renovated luminaires in cases A and C differ due to their replacement schemes: HPS lamps are replaced every 4 years with approximately 2% of spot replacements, whereas LED luminaires are replaced once after 18 years of use. In addition, the power consumption of the LED luminaire in case C is lower than HPS lamp luminaires in cases A and B, and their pole distances differ.

The payback time is calculated by using both a simple and a discounted calculation method when possible. The payback times of cases A and B are low, 8 or 9 and 5 or 6 years, compared to the long lifetime of street lighting installations. In contrast, case C has a long simple payback time that exceeds the time scale of LCC calculations (30 years). It is not possible to calculate the discounted payback time in case C. The case C is not economically justifiable from the payback perspective.

The LCCs are divided similarly in cases A and B. In these cases, the present value of LCCs in the new installations is dominated by the energy costs while the investment costs account about one fourth (Fig. 2). In contrast, the case C is dominated by investment costs, and the share of energy costs is only 14%. In each case, the share of residual value is rather small, 3% to 7%, due to the long time period after which the residual value is discounted.

The operating costs of the new installation differ from the ones of the old installation as seen in Fig. 3. In each case, the new installations consume significantly less energy than the old luminaires, savings ranging from 55%

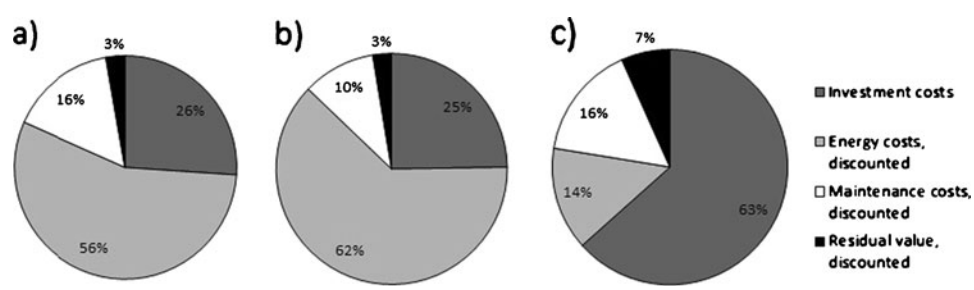

Fig. 2 The division of present values of LCCs in three renewed street lighting installations in Finland: **a** case A, change from HPM to HPS; **b** case B, change from HPM to HPS; **c** case C, change from HPM to LED luminaire

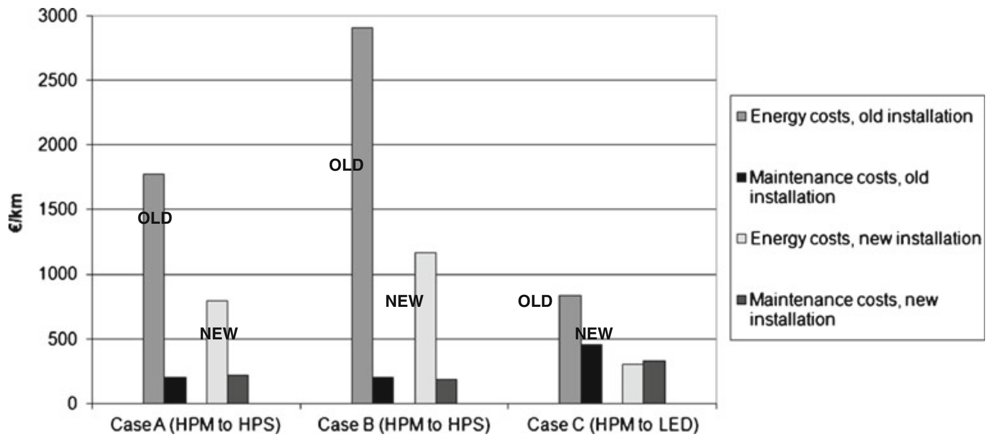

Fig. 3 Annual operating costs of old and new street lighting cases A, B and C

to 64%. Maintenance costs remain in the same order of magnitude (+/−5–10%) in the changes from HPM to HPS lamps. Maintenance costs of case C are reduced by 28%.

The electricity prices paid by the two municipalities are low, 0.082 €/kWh and 0.045 €/kWh, compared to the EU average for industrial consumers, 0.1037 €/kWh (Eurostat 2010), or to the average of municipalities in Finland, 0.095 €/kWh. The electricity prices exclude taxes. The higher the electricity price, the lower are the simple and discounted payback times (Fig. 4).

4.2 Variant cases

Four variants of LED lighting, which include lifetime, price and efficacy development, show the differences in replacement scenarios. The results in Table 6 show that variants 2, 3 and 4 have lower investment costs than variant 1 or case C, both of which are first installed in 2010 when the price of LED luminaire is high. In variants 1, 2 and 3, the operating costs of both old and new installations are higher than the ones of case C, 1,300 and 630 €/km, respectively, due to the higher electricity price of variants. New installation in variant 4 has the lowest operating costs, 510 €/km, due to the lack of luminaire replacements. In addition, variant 4 has clearly the lowest present value of LCCs, 21,930 €/km.

Variants 2, 3 and 4 have both payback times shorter than the time scale of the calculations, 30 years. Variant 4 has the lowest payback times: the simple payback time (6 years) and discounted payback time (7 years).

The present values of LCCs are presented in Fig. 5. Variant 1 causes the highest total costs of all LED cases. Variants 2 and 3 have the overall costs of the same order of magnitude. Variant 4 is the most economic case with 47% lower LCCs compared to case C and 54% lower compared to variant 1.

5 Discussion

To replace an HPM lamp with an updated technology can be an economic solution. Both of the studied replacement options, HPS and LED, reduce the maintenance costs. When HPM lamp luminaires are replaced by HPS lamp luminaires, the investment costs account for about 25%, maintenance costs 10% to 15% and energy costs about 60% of the LCCs. In contrast, changing from HPM to LED technology causes LCCs that are dominated by investment costs (63%) and both maintenance and energy costs account about 15%. The maintenance scheme, power consumption of the luminaire and the electricity price affect the LCCs.

The payback times are less than 10 years in cases replacing HPM with HPS lamps. In contrast, the payback times of replacing HPM with LED luminaires exceed the time scale of the calculations, 30 years, and thus, it never pays off. However, in this case, the electricity price was very low. If the electricity price is higher than the one of the municipality in question, the payback times are reduced. The electricity price of 0.1 €/kWh reduces the discounted payback time of the LED installation to 30 years, and electricity price of 0.2 €/kWh even below 13 years. The

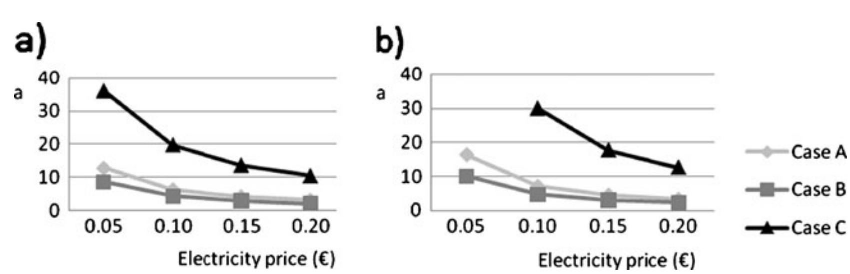

Fig. 4 Simple payback time (**a**) and discounted payback time (**b**) of renovated street lighting cases as the electricity price ranges from 0.05 to 0.20 €/kWh

Table 6 LCC results of variant cases with electricity price of 0.095 €/kWh and including the development predictions of efficacy and price of LED technology

Quantity	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Case C
Investment costs (luminaires)	€/km	26,380	16,760	16,760	10,750	26,380
Operating costs, old	€/km, per annum	2,230	2,230	2,230	2,230	1,300
Operating costs (30 years average), new	€/km, per annum	960	880	920	510	630
Present value of life cycle costs	€/km	48,190	36,050	36,720	21,930	41,600
Simple payback time	a	21	12	13	6	40
Discounted payback time	a	32	16	16	7	–

payback times are also reduced in scenarios where LED luminaires are installed in 2012 or 2015 taking the development in luminous efficacy and price reduction into account. The replacement of HPM lamps by LED luminaires in 2015 is an economic solution even with a very low electricity price. In replacing HPM with LED technology in 2015, the payback times are less than 10 years. If LED luminaires are initially installed in 2012, it has nearly no effect on the LCCs of the renovation whether the group replacement of luminaires takes place in 3 or 18 years.

The calculations include cautious estimates of the LED technology development. If faster and greater development is realised, LEDs will have even shorter payback times due to low investment and operating costs.

There are some uncertainties in the assessment. First, the initial data contain uncertainties in the estimations of inflation and the amount of spot replacements. In addition, the electricity price is valid only for year 2010. The future electricity price is unknown, but it is likely to rise shortening the payback times of energy-efficient lighting installations. Second, the data on current and future LED luminaires contain uncertainties regarding their actual lifetime, lumen depreciation, price development and need of maintenance such as the cleaning of the optics. Third, the estimated residual value can be inaccurate especially for LED luminaires. The residual value is estimated to be 25% of the investment costs according to the Finnish Road Administration, and LED luminaires are three to four times more expensive than HPS luminaires. However, the share of discounted residual value of the total LCCs is low, 7% in the LED case. Fourth, the number of luminaires affects their purchase price. The bigger the batch is, the lower the price. The size of LED street lighting installations remains currently small in Finland, and the purchase price would be lower in installations of hundreds of luminaires.

The LCCs of the three street lighting cases apply only to these three cases. It is not possible to draw an unquestionable conclusion from a limited number of cases.

The results indicate that renewal of street lighting installation results to saving energy and money during the use phase. When HPM lamps are replaced by HPS lamps or LED luminaires, the energy costs drop to about half. Annual maintenance costs remain about the same when HPM lamps are replaced by HPS lamps. High purchase price makes payback times long. In street and road lighting, the buyer is often the user, e.g. the municipality, and thus, an energy-efficient alternative is likely to be implemented despite its high initial investment cost.

It has been discussed whether the economic approach is relevant in a sustainability assessment (Jørgensen et al.

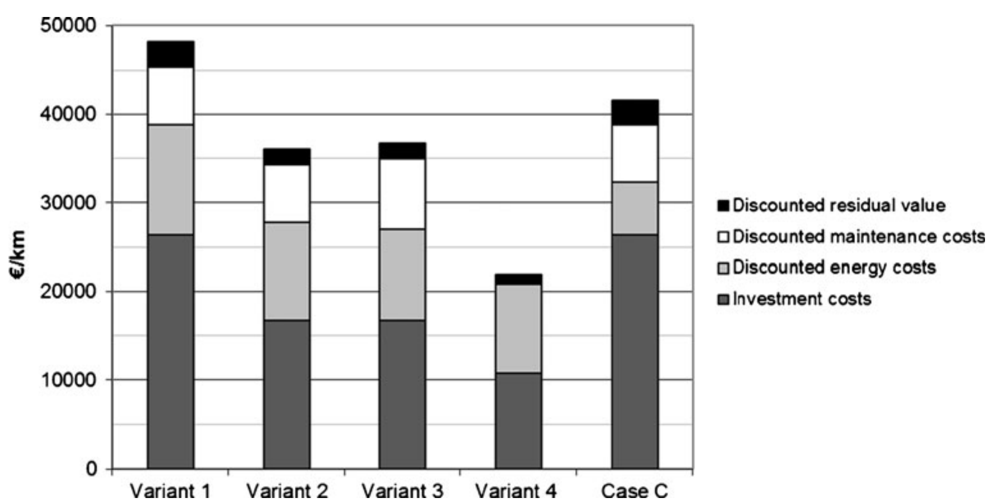

Fig. 5 Life cycle costs (€/kilometre) of LED case variants and case C

2010). It has also been stated that LCC cannot be ignored in sustainability assessment if sustainability is considered to be a three-dimensional factor including environmental, economic, and social aspects (Klöpffer and Ciroth 2011; Swarr et al. 2011). The environmental impacts of high-power outdoor light sources are assessed only in a few LCAs. A comparison of streetlights (Hartley et al. 2009; Dale et al. 2011) reveals that LED luminaires and induction lamp luminaires have lower environmental impact during the life cycle compared to HPS and MH lamp luminaires. Disposal was not included in the LCA. The environmental impacts of LED technology during the manufacture are about three times greater on the average than in HPS lamps mainly due to energy-intensive manufacturing processes and the complex structure of LED luminaire. The lower energy consumption and long lifetime reduce the environmental impacts of LED luminaire. The use phase of streetlights accounts for at least ten times greater environmental impacts than the manufacturing phase, which is a typical result of an LCA of light sources. In addition, the energy source used to produce the electricity has a significant role in environmental impacts. The environmental impacts of LED luminaire are expected to be reduced as the technology develops.

6 Conclusions

Environmental friendliness, cost-effectiveness and foremost the EU legislation are the striving forces behind the ongoing renovations in street lighting installations. The case study shows that renovating street lighting can pay off within 5 to 9 years, which is considered as a reasonable timeframe compared to the long lifetimes of street lighting. The regulatory measures of EU legislation are justified to speed up the penetration of energy-efficient technologies, since the lifetime of outdoor lighting equipment is long and the renewal rate is low.

Currently, LED technology has started to penetrate the street and road lighting market. There are some uncertainties with their suitability in these applications regarding their lifetime, lumen depreciation, and maintenance scheme. More testing and unified information requirements are needed in order to be able to compare LED luminaires. The LCC calculations show that in order for a LED luminaire installation to be economically justifiable, it may be useful to wait 2 to 5 years before replacing current installations. If the technology development is realised, LED streetlights will also be more favourable compared to HPS and MH lamps in terms of environmental impacts.

Decision on the choice of the outdoor light source technology should not be based only on investment costs, since LED luminaires offer savings in operating costs and long lifetime. In addition, LED technology will be improved, and payback times of LED installation will be significantly lowered in 5 years.

The calculation of LCCs of a street lighting installation is essential to see the effects of energy-saving measures in the long run. The LCCs should be more visible and frequently used, since low operating costs compensate high investment costs. More studies are needed regarding the LCCs of street and road lighting in order to compare other light sources than HPS and LED. The lighting design criteria need to be considered, e.g. by optimising the pole placing by simulation. However, this is not always possible in real-life cases. There is a need for a method for taking into account the design criteria quantitatively in the LCC calculations. The scope of the economic assessment could be widened to include other actors than the user. In addition, an assessment including environmental, economic and social aspects is recommended to compare all the aspects of lighting installations and to determine the most sustainable solution.

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